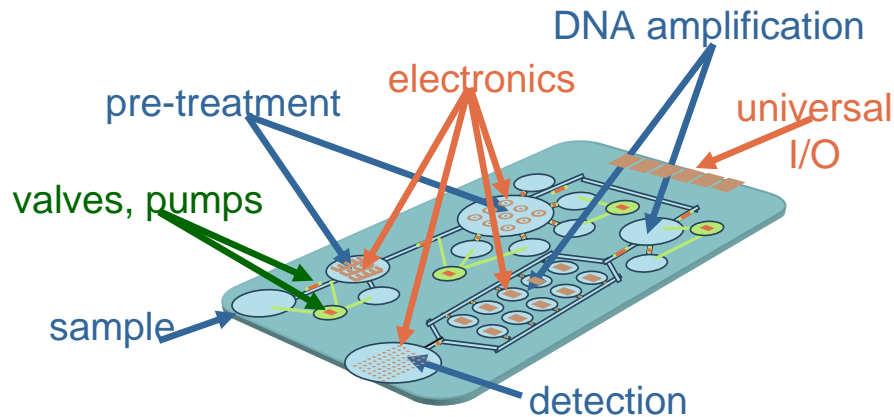


Nature-inspired micro-fluidic manipulation using artificial cilia

A European Specific Targeted Research Project



Philips, NL
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Novel technology for manipulation of fluids on a microscopic scale: lessons from biology

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Modelling and design of ciliary motion.

- I. **Generate new knowledge about the naturally occurring cilia to serve as the reference for the technical, artificial cilia processes and technology.**
- II. **Control of the movement of individual cilia: find ways of mimicking the asymmetric movement of natural cilia.**
- III. **Contribution to the developing of a process to make cilia covering a surface**

Generate new knowledge about the naturally occurring cilia

- ✓ Review of all existing ways of moving water on micro scale in biology
- ✓ Develop a method to extract relevant information from biology and transform it into engineering domain.
- ✓ Show the possibilities to achieve the properties of living cilia by technological means.

Catalogue of the liquid-moving mechanisms in biological systems

We have found:

- Great diversity of forms, but limited diversity of mechanisms
- Unjustified and unwarranted complexity, if we decide to copy natural phenomena

Biomimetics: Interpreting *Versus* Copying

1. Knowledge/information transfer from biology to technology is not trivial.
2. Interpretation rather than translation:



=



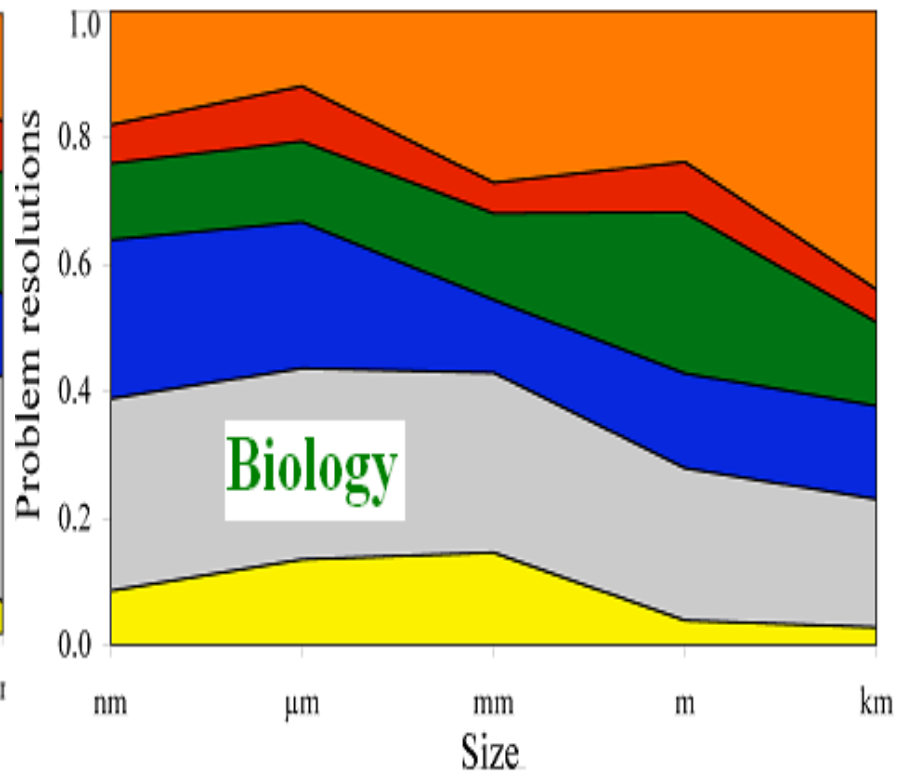
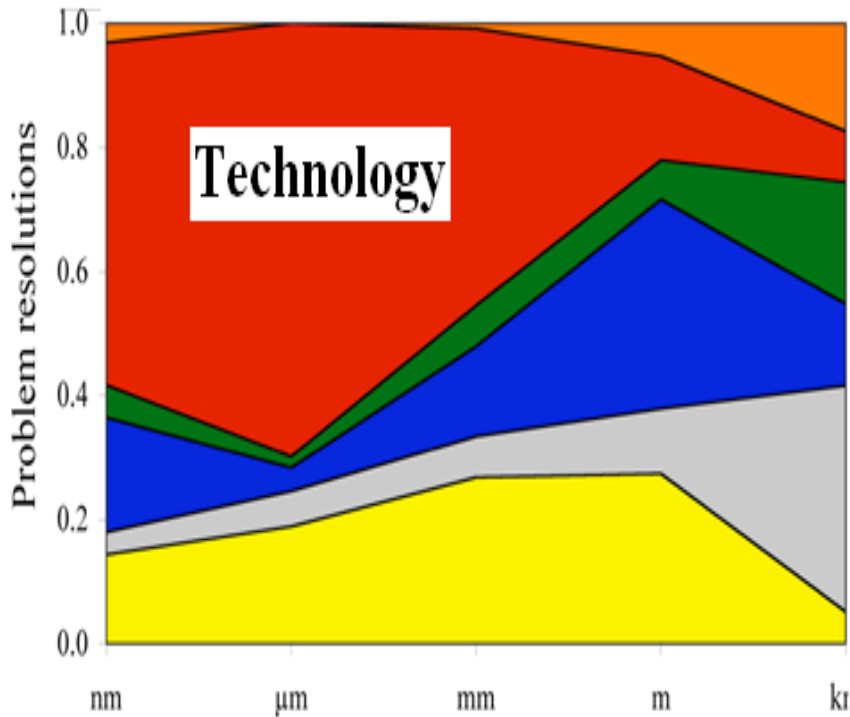
English

Russian

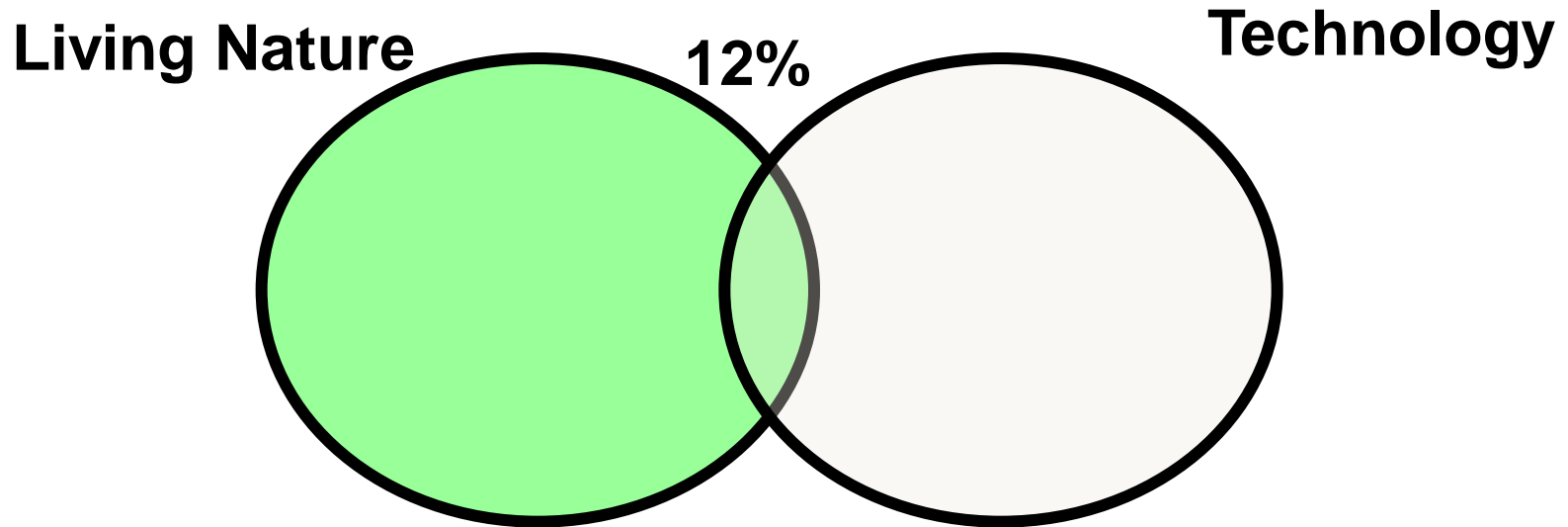
Technology and Nature: two opposite strategies

Technology solves the problems in materials and energy;
Biology – in information and structure

- Information
- Energy
- Time
- Space
- Structure
- Substance



Different strategies for providing the functions is the main resource for Biomimetics



Types and Prototypes

Animate biological cilia	Artificial inanimate cilia we would rather like
<ol style="list-style-type: none">1. Structure: radial-symmetrical due to 3-D operation2. Functionally universal3. Shape of a cilium is typically round4. Type of actuation: metachronic reciprocation5. Combined with the other types of actuation and/or with the hierarchically organised geometrical effects	<ol style="list-style-type: none">1. Structure: bi-laterally symmetrical or asymmetrical due to 2-D operation2. Functionally specialised3. Shape of a cilium is flat4. Type of actuation: typically all types of rotation. ?5. ?

**We want to see features of
living systems in technology,
BUT...**

copying biological prototypes makes
our product extremely complex and
expensive.

How to extract relevant information from biology and transform it into engineering domain?

Our solution:

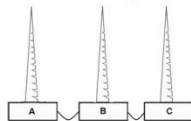
Dichotomic catalogue and tables of the essential parameters

Allow the possibilities to achieve the properties of living cilia by technological means.

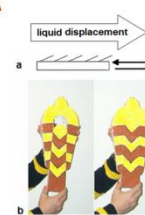
Classification of the parameters of the cilia-like structures

Cilia Basement		DYNAMIC (MOVING)														STATIC (NOT MOVING)											
		ACTIVE						PASSIVE								ACTIVE						PASSIVE					
		Flexible			Rigid			Flexible				Rigid				Flexible			Rigid			Flexible			Rigid		
		Plastic		Elastic	Plastic		Elastic	Plastic		Elastic	Plastic		Elastic	Plastic		Elastic	Plastic		Elastic	Plastic		Elastic	Plastic		Elastic		
		Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm	Symm	Asymm				
DYNAMIC (MOVING)	ACTIVE	Flexibl	Plastic																								
		Flexibl	Elastic																								
		Rigid	Fragmented																								
	PASSIVE	Flexibl	Plastic																								
		Flexibl	Elastic																								
		Rigid	Continuous																								
STATIC	ACTIVE	Flexibl	Plastic																								
		Flexibl	Elastic																								
		Rigid	Continuous																								
	PASSIVE	Flexibl	Plastic																								
		Flexibl	Elastic																								
		Rigid	Continuous																								

“Metachrone” actuator with morphologically asymmetrical cilia



“Crawly” – another ciliar actuator (a - side view; b - model showing longitudinal segmentation – the chevrons show the displacement of segmented parts). The central part of the device moves to-and-fro relative to lateral part. As liquid at the microscale level possesses high apparent viscosity, it will be moved by the rigid asymmetrical cilia, which cover all the surface (moving and non-moving parts) of “Crawly”. The central moving part is made as a wedge for easier moving.



“Creepy” – a ciliar actuator. (a - side view shows segments A, B, C, rigid “cilia” and elastic elements connecting segments; b - model in stretched and contracted positions – segments are painted in contrasting colours).

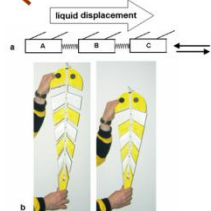


Table 3: Natural and artificial distributed/modular effectors: the field of logical possibilities.

- 1 – Flat worms (e.g., *Planaria maculata*).
- 2 – Most of ciliated infusorians (e.g., *Paramecium caudatum*), and flagellated organisms (e.g., *Volvox globator*).
- 3 – Infusorians with cirri (e.g., *Stylonichia mytilus*).
- 4 – Cilia as a part of macro-organism, (e.g., human lung cilia.)
- 5 – Cilia and membranelli of the sessile aquatic animals (e.g., *Stentor coeruleus*).
- 6 – Artificial device with passive rigid asymmetrical cilia and active flexible elastic actuating basement (“Creepy”).
- 7 – Artificial device with passive rigid asymmetrical cilia and active rigid fragmented actuating basement (“Crawly”).

- 8 – Artificial device with passive morphologically-asymmetrical movable cilia with active fragmented actuating basement with backlash providing a metachronal wave (“Metachrone”). Artificial entities are represented by macro-scale devices.
- 9 – Shoe brush
- 10 – Hair comb
- 11 – Rasp, cross-country skis
- 12 – Rubber door mat with bristles

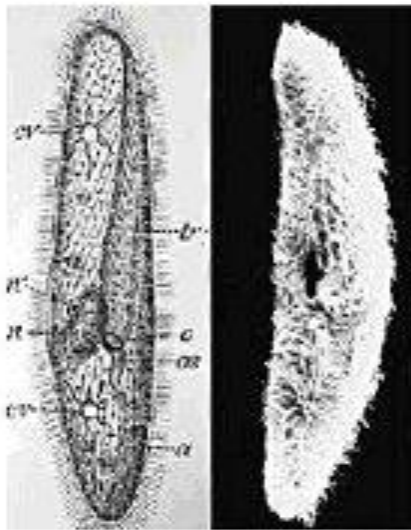
Control of the movement of individual cilia: find ways of mimicking the asymmetric movement of natural cilia

- ✓ Asymmetric movement is achieved by asymmetric structure of artificial cilium
- ✓ Metachronic wave can be achieved by the cascade motion of the fragmented ciliated surface/basement.
- ✓ Metachronic and asymmetric beating of artificial cilia is achieved with the help of rotational actuation instead of extremely complex natural mechanisms.

Living Cilia

Natural cilia is very complex, actually they are linear electric motors. Copying? – **Mission impossible!**

Interpreting?



(a)



(b)



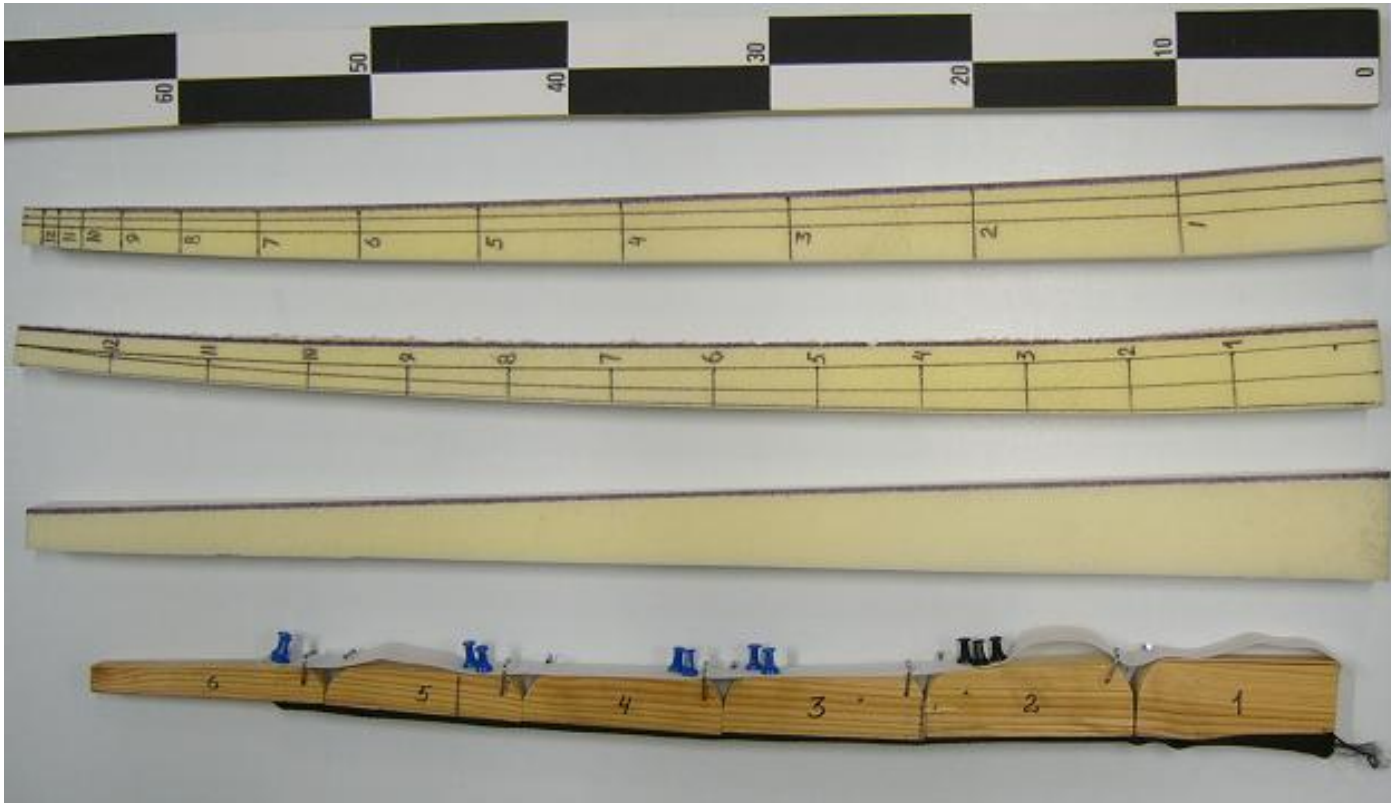
Power stroke



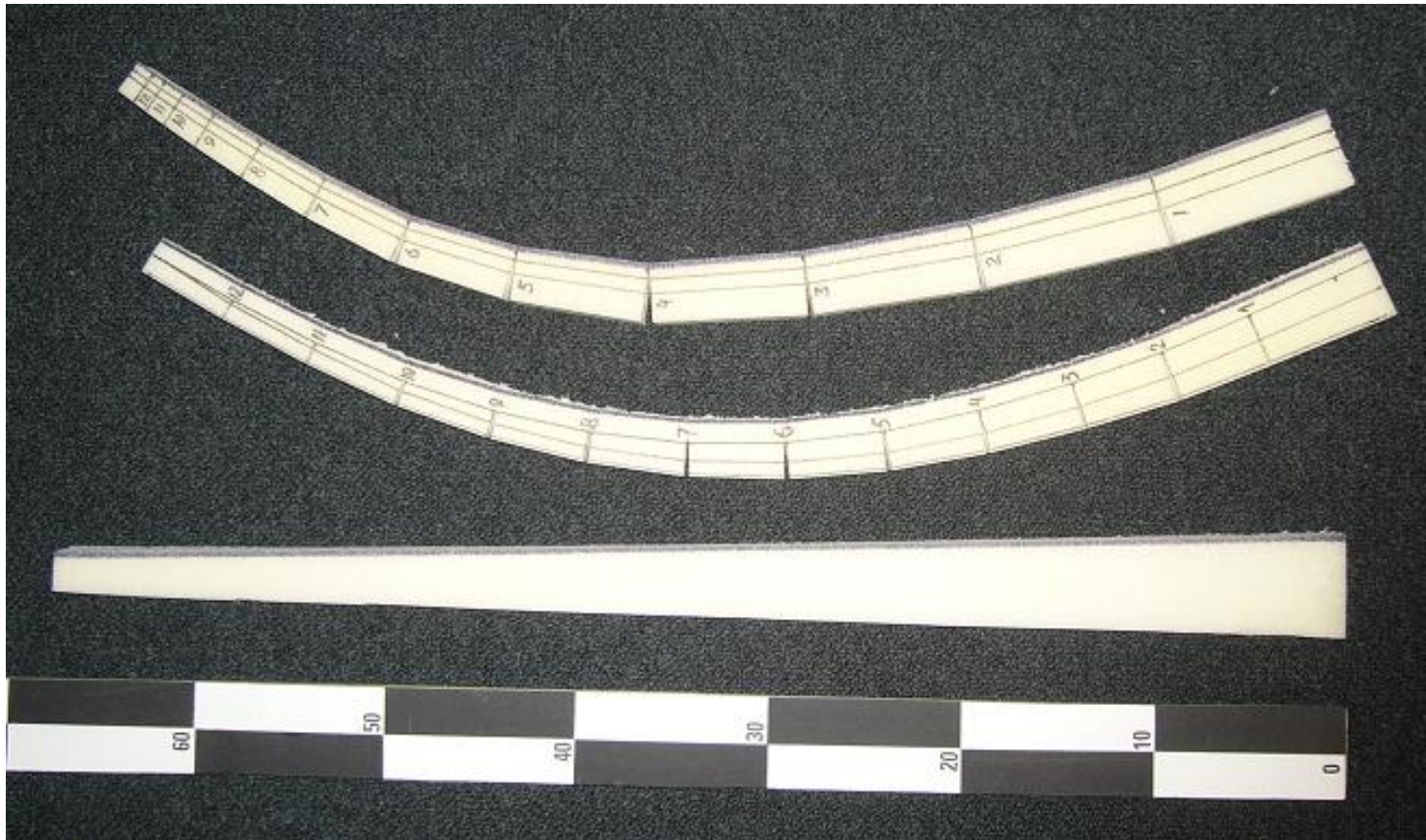
Recovery stroke

(c)

Our solutions: Models of flexible cilia: asymmetrical fragmentation with elastic joints



Flexible cilia: uniform and non-uniform fragmentation



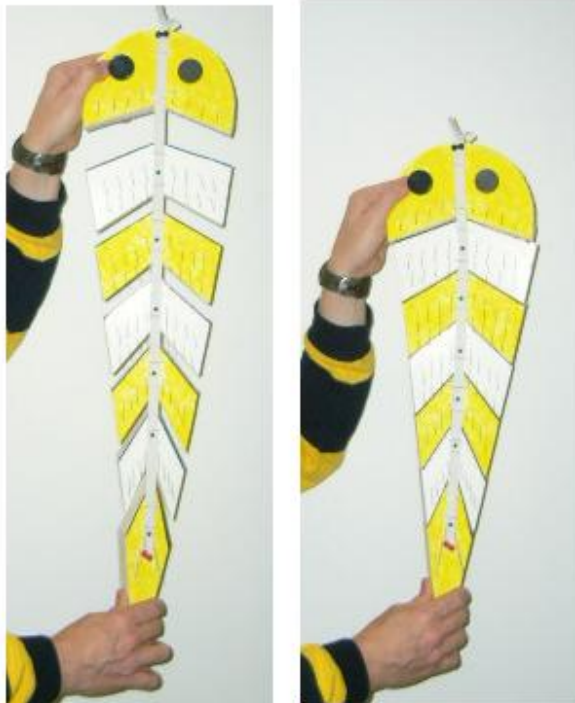
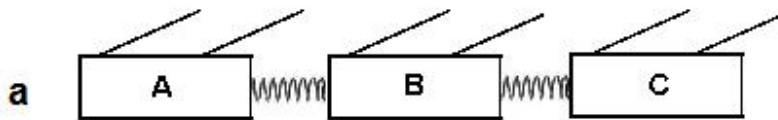
Contribution to the developing of a process to make cilia covering a surface

Our solutions: ciliated systems with the movable basement and rigid, fixed, asymmetrically positioned, passive cilia

In other words: if we cover dynamic surface with the numerous asymmetrical uniform structures (e.g., “needles”), any movement will provide onward motion of an object along this surface

Creepy and Crawly

Creepy

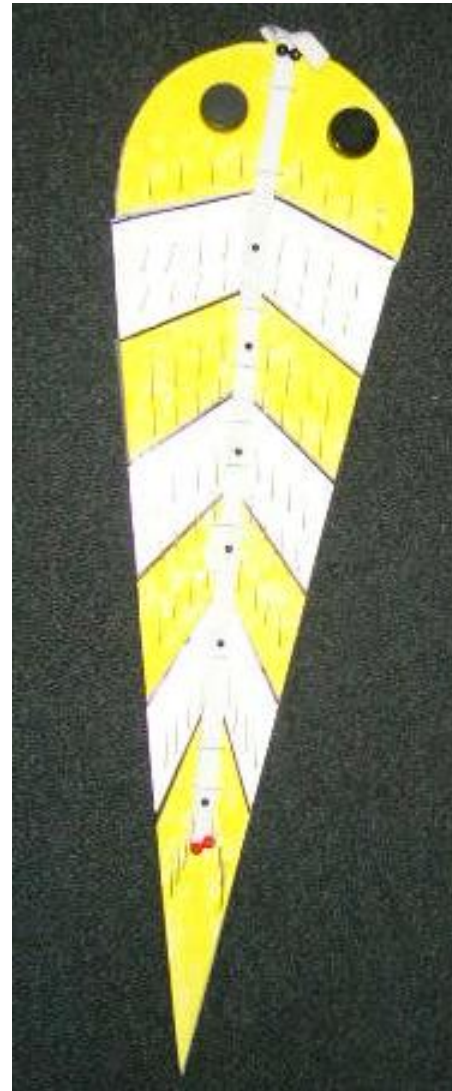


“CREEPY” – a ciliar actuator. (a - side view shows segments A, B, C, rigid “cilia” and elastic elements connecting segments; b - model in stretched and contracted positions – segments are painted in contrasting colours).

Types of basement fragmentation



Fragmentation of the basement perpendicular to the longitudinal axis with the elastic joints and rigid static cilia: “CREEPY”



Crawly



“Crawly” – another ciliar actuator (a - side view; b - model showing longitudinal segmentation – the chevrons show the displacement of segmented parts).

Longitudinal fragmentation of the basement with the elastic joints and rigid static cilia: “CRAWLY”



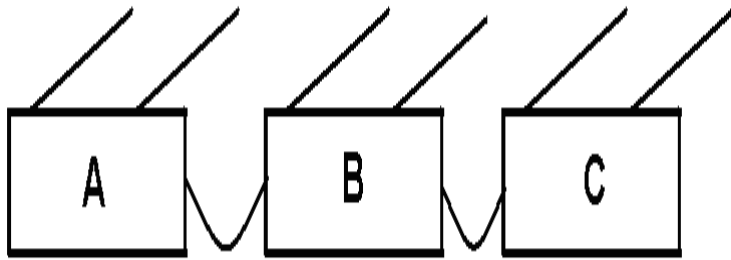
**Control of the movement of individual cilia:
how to find ways of mimicking the asymmetric
movement of natural cilia?**

Our solutions:

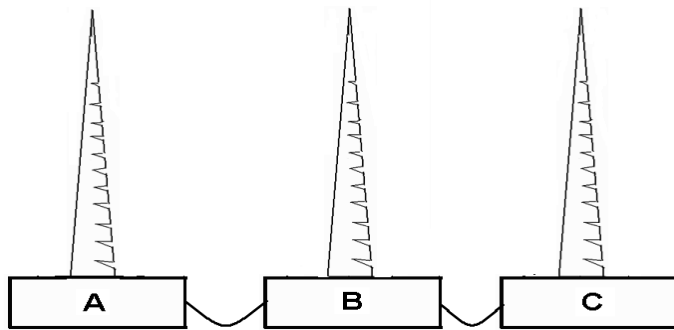
1. Metachrone
2. Rotochrone

METACHRONE:

Plastic joints instead of elastic ones



Metachronal wave is allowed by the looseness of the joints (A, B, C – segments with soft plastic connection providing cascade actuation due to slack).



“Metachrone” actuator with morphologically asymmetrical cilia.

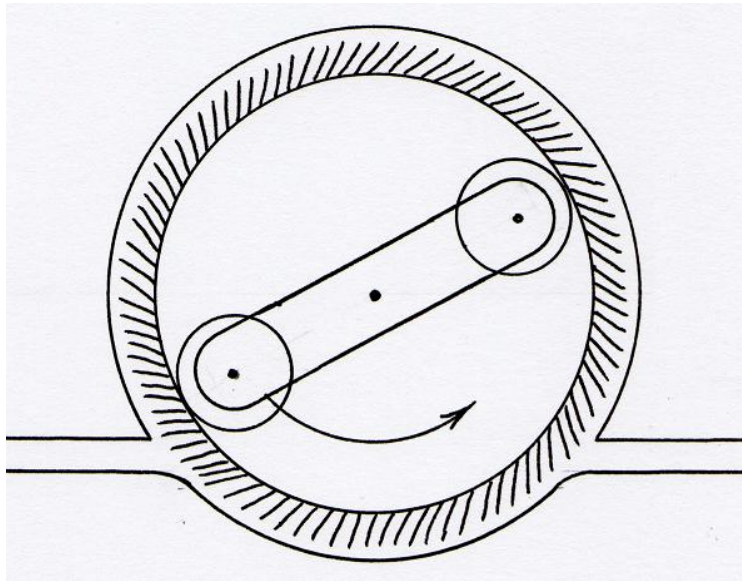


How to provide metachronism – travelling wave – for ciliated actuators?

Our solutions:

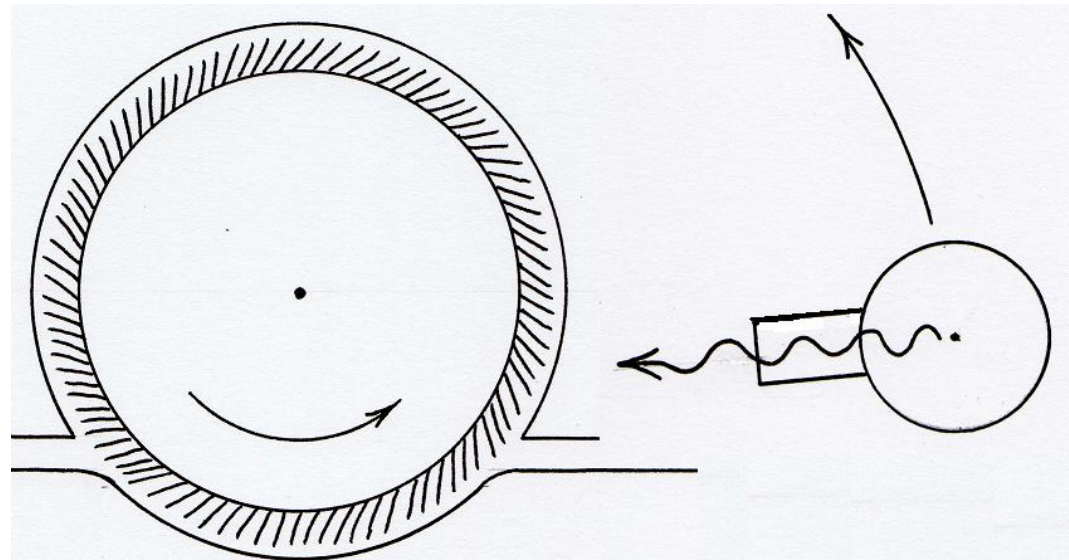
Adding the basic and typical motion from engineering – ROTATION – to ciliar reciprocative actuator, we can achieve travelling wave.

A combination of rotating and reciprocal movement for creating travelling wave



Internal mechanical driver with rollers – difficult to implement at the micro-scale.

External orbiting field driver with narrow beam activating field-sensitive basal membrane or/and cilia



Environment, conditions and the entire context in Biomimetics: steps to follow

- Making catalogues of parameters of the environments/liquids and other media, which are in contact with the liquids (interfaces, inclusions and their combinations)
- Considering the conditions for operation (e.g., duration of action, reliability, etc.)
- Context: customer, domain of application, single sample or mass production, cultural limitations etc.

CONCLUSIONS

- I. **New knowledge about the naturally occurring cilia to serve as the reference for the technical, artificial cilia processes and technology.**
 - Great diversity of forms in life, but low diversity of mechanisms
 - Unjustified and unwarranted complexity, if we decide to copy life phenomena

- II. **Control of the movement of individual cilia: find ways of mimicking the asymmetric movement of natural cilia.**
 - Control is provided by the structural and functional asymmetry of artificial cilia
 - Movable surface increases the effectiveness of the actuation process and can be achieved by segmentation and/or materials with different plastic/elastic properties
 - Metachronic and asymmetric beating of artificial cilia is achieved with the help of rotational actuation instead of extremely complex natural mechanisms.

- III. **Contribution to the developing of a process to make cilia covering a surface**
 - Coverage of the surface with the asymmetrical metameric stiff elements
 - Movable fragmented surface/basement can solve the problem of controllable actuation of liquid media